EPA-PNL-2077

Palmer Hough/DC/USEPA/US

06/26/2012 06:11 PM

To: aicher.rebecca, Barbara Butler, Bill Dunbar, Cara Steiner-Riley, Christopher Hunter, Dave Athons, David Allnutt, Glenn Suter, Hanady Kader, Heather Dean, Heidi Nalven, Jason Todd, Jeff Frithsen, Jenny Thomas, Jim Wigington, Joe Ebersole, Judy Smith, Julia McCarthy, Kate Schofield, Marianne Holsman, Mary Thiesing, Michael Szerlog, Palmer Hough, Phil North, Rachel Fertik, Richard Parkin, Sheila Eckman, Tami Fordham

cc

bcc

Subject: Fw: More EBD Review White Papers

Folks:

Attached are two more white papers prepared by the AK Conservation Foundation regarding the PLP EBD. These two papers deal with seismic and hydrology issues.

Thanks, Palmer

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----- Forwarded by Palmer Hough/DC/USEPA/US on 06/26/2012 09:09 PM -----

From: Samuel Snyder <snyder.bristolbay[redacted] PERSONAL PRIVACY
To: Palmer Hough/DC/USEPA/US@EPA
Date: 06/26/2012 07:16 PM
Subject: More EBD Review White Papers

Palmer,

I hope this email finds you doing well. I have attached two more EBD review white papers - seismic and hydrology. These got a bit delayed due to Watershed Assessment review work. We have two more on the way: Water Quality, Fisheries Escapement and PHABSIM. I should have the first two to you by the end of the week.

Feel free to contact me if you have any questions.

Best
Sam

Pebble Seismic Critique (Final).pdf 2012.05.25.EBD.Hydro.pdf

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"I shall never look upon a river without urgent consideration of the possibilities of finding fish somewhere in it." Roderick Haig-Brown

Go Green, Keep it on your screen! Think before you print!

Samuel Snyder, PhD
Alaska Conservation Foundation
Director Bristol Bay Watershed and Fisheries Protection Campaign
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Critique of Pebble Limited Partnership's Seismic Hazard Assessment

Dr. Bretwood Higman, Ground Truth Trekking

Executive Summary

The seismic hazard assessment presented in Pebble Limited Partnership's Environmental Baseline Document (PLP 2012 Ch 6) is flawed. It draws strong, optimistic conclusions from weak evidence, and relies on geologic arguments inconsistent with observed evidence. It misrepresents existing research and fails to use key data sets that PLP has in-hand to inform the analysis. A major fault, the Lake Clark Fault, passes near the Pebble prospect. No published studies establish this fault's location or seismic activity near the prospect, and the hazard assessment presents no effort to positively determine its location. The hazard assessment fails to consider minor faults or induced seismicity. Without further study, the hazard posed by earthquakes is impossible to determine.

Introduction

Mineral exploration and mining claims have recently expanded a great deal in the Bristol Bay area. Of these, the Pebble prospect is the most advanced exploration project. This world-class copper, gold, and molybdenum ore body contains an estimated 10.8 billion tons of ore (Wardrop-NDM 2011) and will leave behind billions of tons of waste material that will require reliable containment in perpetuity, withstanding natural hazards such as floods and earthquakes. Tailings will likely be stored behind a network of earthen dams, some possibly over 700 feet tall (DNR 2006, Wardrop-NDM 2011).

Future earthquake risk at the Pebble prospect is unknown. Similar facilities are usually engineered to withstand the strongest earthquake likely in 10,000 years (ICOLD, 2008), although even larger earthquakes may be relevant to engineering perpetual storage facilities. Because of the long time frames involved, hazard assessment must include faults that produce earthquakes only very infrequently, where fault activity is more difficult to study. These studies have not been conducted in the Pebble area. The proposed open pit mine, buildings, pipeline and port (Wardrop-NDM 2011) would all be vulnerable to a potential earthquake. Their failure could cause loss of life and environmental harm. However, the greatest potential threat to the region would be failure of a tailings dam. A dam failure could release a plume of acidic, metal-laden water and mine tailings into downstream waterways, threatening drinking supplies and fisheries resources (TNC 2010).

The severity of shaking during an earthquake depends both on the size and proximity of the earthquake. If the possibility of a large earthquake close to mine facilities cannot be ruled out, there is a threat of exceptionally strong shaking and dam failure. Therefore, it is critical to locate all the faults in the area and assess their activity so that structures can be engineered for the actual threat. Lacking accurate data, the conservative assumption must be that a large active fault passes directly beneath mine facilities.

Regional Geology

Alaska is the most seismically active state in the nation. The Pacific Plate is diving beneath Alaska, driving frequent earthquakes and feeding volcanoes in Southcentral Alaska, along the Alaska Peninsula and through the Aleutian Islands. The North America tectonic plate is fragmented in Alaska, with one block of crust in Southcentral Alaska (Haeussler, 2008) and another in the Bering Sea (Makey et al., 1997). These blocks appear to be moving independently from the rest of North America, fracturing and deforming the crust between them. The complex relative motion of these crustal fragments drives earthquakes on faults between them.

The region around Pebble sits between these shifting blocks of crust, so stress that could trigger earthquakes is likely accumulating in the region. This is supported by the fact that a few shallow earthquakes have been observed within a few tens of miles Pebble over the past few decades (USGS Earthquake Hazard Program catalog). Though none of these were large, they indicate forces are in place to drive earthquakes.

Environmental Baseline Document (EBD) Seismic Hazard Assessment Methodology

No original work by seismologist or neotectonics expert is presented by PLP in this baseline document. PLP's (2012 Ch 6) seismic hazard assessment methodology consists almost entirely of reviewing existing research, most of which relates to the tectonics and seismicity of Southern Alaska and Cook Inlet, but not to the mine area or Lake Iliamna. The analysis focuses on the location and possible activity of the Lake Clark Fault. It does not analyze the potential hazard posed by smaller faults such as those PLP (2012 Ch 3.7.3) has already identified near and beneath proposed facilities, nor does it address the significant induced seismicity hazard.

PLP does not analyze or mention the LiDAR (high-resolution laser altimetry) and Aeromagnetic surveys it possesses of the area.

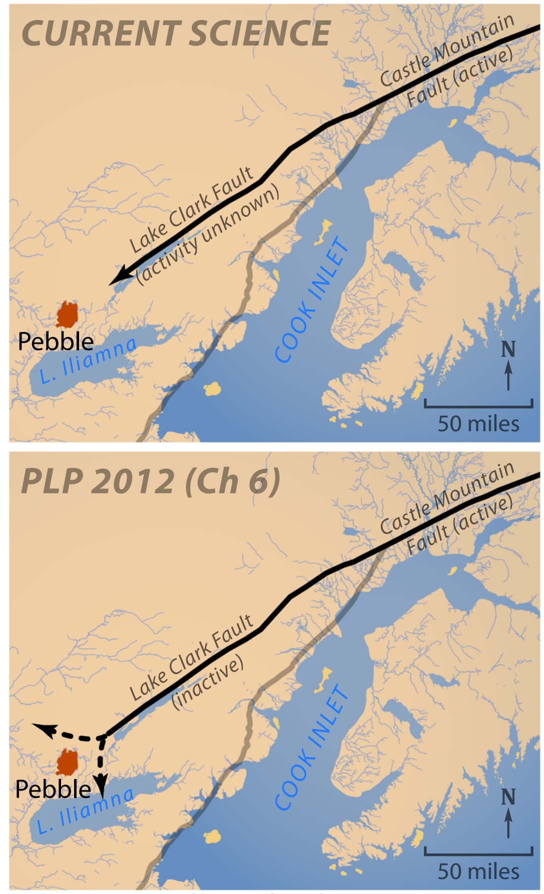

Figure 1: PLP (2012 Ch 6) concludes that the Lake Clark Fault is inactive, and veers away from the mine site. This conclusion is not supported by either PLP's work, or existing literature - the fault's location near Pebble, and its activity, are unknown.

Discussion of EBD Results

One major local fault, the Lake Clark Fault, runs near the Pebble prospect. The PLP (2012 Ch 6) seismic hazard assessment focuses on the potential risk posed by this fault and asserts that there is no significant earthquake risk.

This hazard assessment is flawed. It draws strong conclusions from weak evidence, and relies on geologic arguments inconsistent with observed evidence.

The document contains some 30,800 pages, but the section dealing with seismic hazard assessment is only four pages long. It is found in Section 6.6.2 (summary and conclusions in 6.7) of the EBD. It refers to three figures (Figures 6-51 through 6-53).

The assessment suffers from the following flaws:

1. PLP (2012 Ch6) concludes the Lake Clark Fault cannot pass near the mine site. This conclusion is drawn from several flawed lines of reasoning:

    a. The Lake Clark fault may end northwest of the mine prospect.

    b. If the fault continues, it is assumed to follow glacial flow.

    c. Bedrock near the prospect is assumed to be too strong for a major fault to break it.

2. Lack of evidence of activity is confused with evidence of inactivity.

3. Key data are not examined.

4. Local faults and induced seismicity are not considered.

1. Where is the Lake Clark Fault?

PLP (2012 Ch 6) concludes: *"The seismic hazard associated with crustal faults in the mine study area is not considered to be significant as the ground accelerations generated by earthquakes decrease the farther the distance from the epicenter."*

Since PLP (2012 Ch 6) identifies the Lake Clark Fault as the major seismic hazard in the area, PLP must be assuming that the Lake Clark Fault is far from the Pebble prospect, though this is not explicitly stated. Several flawed lines of reasoning presented in the EBD appear to support this conclusion.

1a. Where Does the Lake Clark Fault End?

The Lake Clark Fault is a major fault connected to the well-known Castle Mountain fault in south-central Alaska. It trends northeast to southwest, from near Beluga, through the Tlikakila River valley, and then along Lake Clark (Nelson et al., 1983). The fault has not been mapped further southwest than this. Taking the simplest assumption, that the fault continues on its mapped course, it would pass through or near the Pebble prospect (Figure 1).

PLP (2012 Ch 6): *" Published information indicates that the Lake Clark fault terminates at the western end of Lake Clark, over 15 miles from the eastern edge of the mine study area. This distance is based on a recent study by Haeussler and Saltus (2004) who used aeromagnetic data to refine the position of the western end of the fault."*

This is inaccurate. Haeussler & Saltus (2004) stopped mapping the fault where their survey data ended. They did not suggest that the fault ended at this point. PLP (2012 Ch6) acknowledges the fault may continue, but implications are not discussed. Haeussler & Saltus (2004) show the Lake Clark Fault has moved 16 miles at Lake Clark. This motion on the fault (offset) cannot simply end – the fault must either extend further, or transition into some other fault.

1b. Do Faults Follow Glaciers?

PLP (2012 Ch 6): *"The mapped direction of primary glacial advance, shown on Figure 6-53, suggests that any potential extension of the Lake Clark fault may pass north and/or east of the mine study area, and would not cross the mine study area."*

PLP (2012 Ch 6) infers this from Hamilton and Klieforth's (2010) surficial geology study of the area, which mentions that Pleistocene glaciers followed the Lake Clark fault along part of its length. Hamilton and Klieforth's work does not imply that faults always follow glacial paths.

Glaciers frequently cross faults, including the Lake Clark Fault further to the northeast. Many active faults are not parallel with landscape features (such as ridges and valleys) that typically control glacial flow (e.g. the Seattle Fault, Sherrod et al. 2008). For the Lake Clark Fault to track with glacial advance, it would have to make an abrupt, unusual turn (Figure 1). PLP presents no evidence that the fault actually makes this turn.

1c. Can Faults Cut Through Volcanic Bedrock?

PLP (2012 Ch 6): *"The mine study area is located on plutonic outcrops (some of batholithic scale) that likely provide resistance to crustal fracture."*

This statement suggests that no large fault (such as the Lake Clark Fault) could pass near the mine because there are large continuous bodies of rock. This is inaccurate. Major faults including the Lake Clark Fault further northeast and the Denali fault in the Alaska Range cut through plutonic volcanic rocks.

Near the Pebble prospect, PLP (2012 3.7.3) mapped a number of faults, demonstrating that the rock is susceptible to faulting. Detailed information on these faults can be found in the EBD, chapter 3. They are depicted in figure 3-6a.

2. Is the Lake Clark Fault Active?

PLP (2012 Ch 6) claims the Lake Clark Fault is inactive. In reality, very little research has been done on Lake Clark Fault's activity.

PLP (2012 Ch 6): *"The Lake Clark fault is considered inactive by the USGS."*

The USGS does not classify Lake Clark Fault as inactive. In fact, the USGS maintains no database of inactive faults. Faults are generally classified based on the most recent evidence of activity on the fault (e.g. Plafker et al. 1994), since it is nearly impossible to establish that a fault is totally inactive and incapable of producing future earthquakes.

In support of this claim that the fault is classified as inactive, PLP (2012 Ch 6) references a USGS publication that reviews information on the Lake Clark Fault, but does no original work on the fault. The USGS publication itself is ambivalent in its conclusion: *"...if further geologic studies find no evidence for surface faulting, it would be difficult to conclude that a significant seismic hazard exists from crustal faults in the area."*

The most recent published research on the activity level of the Lake Clark Fault is by Koehler and Reger (2011). They studied a location 150 miles from the Pebble prospect, on the northeastern section of the fault. This preliminary reconnaissance report suggests no motion in the past ten to sixty thousand years, but possible motion in the last one-hundred thirty thousand years. Tectonic processes change on time-scales of millions to hundreds of millions of years, so any fault active in the past few hundred thousand years is likely active today. The authors explicitly acknowledge the limitations of the work: *"...distributed slip on unrecognized structures and dense vegetation that might obscure tectonic features along the Lake Clark fault could limit assessment of tectonic activity."* They also note: *"The paleoseismic history of the western part of the Lake Clark fault remains unknown."* This part with no known history or activity is the section of the fault that passes near or through the Pebble prospect.

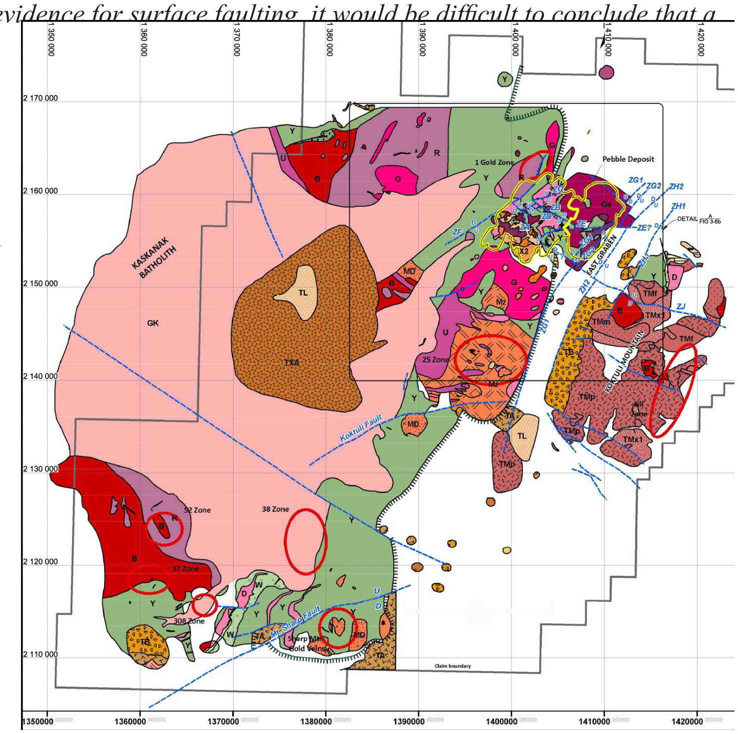

Figure 2 (PLP 2012 3.7.3, figure 3-6a): PLP maps the bedrock near Pebble Prospect. Blue lines are small faults in the area. The deposit is outlined in yellow near the northeast corner of the map.

Studying multiple areas on a fault, and choosing study sites near an area of concern, is important. Evidence of major earthquakes can be missed, leading active faults to appear inactive. Some earthquakes don't rupture the ground surface at all, and therefore don't leave obvious surface evidence. Many earthquakes leave surface evidence that is very subtle and can be missed even in detailed study. For example, in 1999 an "inactive" fault in southern California produced a magnitude 7.1 earthquake and ruptured the desert ground surface for 25 miles (Rymer et al., 2002). Recently another fault in California, the Kern Canyon Fault, long thought inactive, was shown to have produced large earthquakes in the past few thousand years (Nadin and Saleeby, 2010).

Existing research does not provide adequate evidence to estimate the activity level of the Lake Clark Fault at the Pebble prospect, where the fault has not been mapped or studied.

3. Key Data are Not Examined

Some of these questions regarding the Lake Clark Fault could potentially be addressed using data PLP has in-hand. PLP has collected LiDAR (high resolution topographic data) and aeromagnetic surveys in the area of the mine site. Both are useful for seismic hazard investigation. Aeromagnetic surveys sometimes show the location of faults, and were used to map the portion of the Lake Clark Fault immediately to the northeast of the area in question (Haeussler and Saltus, 2004). LiDAR data has often proven critical for identifying subtle deformation of the ground surface caused by past earthquakes (e.g. Sherrod et al. 2004, Kelsey et al. 2008). Despite collecting that data, PLP (2012 Ch 6) did not present a tectonic analysis of either data set in the EBD, and this data is not available for independent review.

4. Minor Faults are Not Considered

PLP's (2012 3.7.3) geologic map (Fig. 2) shows a number of small faults cutting bedrock in the vicinity of the mine. These faults are not discussed in the PLP (2012 Ch 6) seismic hazard assessment.

Minor faults are unlikely to create very strong earthquakes, but if an earthquake happened on a fault located directly underneath tailings dams or other structures, it could be damaging.

In addition to natural earthquakes on these faults, there is the possibility that increased weight and groundwater pressure imposed by a tailings impoundment could change the stress field in the earth enough to cause a local earthquake. An analysis of past man-made earthquakes (McGarr et al. 2002) shows that structures spanning multiple kilometers, like those proposed at Pebble (DNR 2006, Wardrop-Northern Dynasty, 2011), can result in earthquakes over magnitude 5. These earthquakes are most likely in cases where the force exerted by human activities lines up with geologic stresses and existing faults (McGarr et al. 2002).

PLP (2012 3.7.3) maps several parallel small faults that have allowed a wedge of bedrock to shift downward, a "graben," within the mine area. In their 2006 mine plan (DNR, 2006), a tailings dam is planned directly over this graben. This is a scenario where a fault might be activated by a human activity. Grabens form where the earth stretches, and large blocks of bedrock sink downwards along faults. Since the weight of a tailings facility would apply increased downward pressure to this graben, it has an increased chance of triggering an earthquake (McGarr et al. 2002).

Conclusions

The seismic hazard assessment contained in the PLP EBD misrepresents existing work and relies on faulty arguments. The Lake Clark Fault is a major crustal fault that is likely to pass near or through the Pebble Mine prospect. Both the location and activity of this fault are little studied. Without further study, the likelihood of an earthquake and the potential intensity of shaking are impossible to determine. Due to the nature of the proposed project, the seismic hazard assessment must consider earthquakes that are rare, and without precedent in the immediate past.

PLP's (2012 Ch 6) assessment provides no new research on this issue. It does not analyze relevant existing data. The conclusions consistently downplay potential seismic hazards, and they do not provide convincing evidence in support of those conclusions. Original work is necessary to accurately assess seismic risk at the prospect.

Annotated Bibliography

Referenced publications plus additional publications that specifically bear on seismicity in the Pebble area.

Publication	Referenced in Seismic Hazards section of EBD*	Notes
R. L. Detterman, B. L. Reed, 1980: Stratigraphy, Structure, and Economic Geology of the Iliamna Quadrangle, Alaska; Geological Survey Bulletin 1368-B.	No	Maps several faults of unknown significance near the Pebble Prospect. No information on the location of the Lake Clark Fault.
DNR (Dept. of Natural Resources), 2006: Pebble project initial application for certificate of approval to construct a dam. Tailings impoundment A and Tailings impoundment G. http://www.dnr.state.ak.us/mlw/mining/largemine/pebble/water-right-apps/index.cfm	N/A	Provides specific engineering diagrams of dams from Northern Dynasty's 2006 mine plan. Includes 3 dams, with heights of about 400 feet (impoundment G), and two over 600 feet (impoundment A).
P. J. Haeussler, 2008: An Overview of the Neotectonics of Interior Alaska: Far-Field Deformation From the Yakutat Microplate Collision; Geophysical monograph vol. 179, p. 83-108.	No	Outlines a model for southern Alaska tectonics wherein southcentral Alaska rotates counterclockwise, driven by subduction of the Yakutat Microplate.
P. J. Haeussler, R. W. Saltus, 2004: 26 km of Offset on the Lake Clark Fault Since Late Eocene Time; U.S. Geological Survey Professional Paper 1709–A.	Yes	Maps the Lake Clark Fault based on Aeromagnetic data, showing 26 km (16 mi.) offset.
P. J. Haeussler and C. F. Waythomas, 2011: Review of the Origin of the Braid Scarp near the Pebble Prospect, Southwestern Alaska; USGS Open-file Report 2011-1028.	Yes	Primarily presents evidence that a single trench near on the Braid Scarp does not show evidence of an active fault. Also presents a review of existing literature on the Lake Clark Fault.
T.D. Hamilton, R.F. Klieforth, 2010: Surficial Geologic Map of parts of the Iliamna D-6 and D-7 Quadranagles, Pebble Project Area, Southwestern Alaska, DNR DGGS Report of Investigations 2009-4.	Yes	Maps surficial geology near Pebble, including several lineaments interpreted as unrelated to seismic activity.
ICOLD (International Commission on Large Dams), M. Wieland, 2008: Large Dams the First Structures Designed Systematically Against Earthquakes, 2008 World Conference on Earthquake Engineering.	N/A	Reviews history and criteria for designing dams against earthquakes. States that typically the "Maximum Credible Earthquake" is defined as having a statistical return period of 10,000 years. Note this is looking at all dams – it may be that higher standards would apply to tailings facilities that must stand for longer than 10,000 years.

D. S. Kaufman, K. B. Stilwell, 1997: Preliminary evaluation of emergent postglacial shorelines, Naknek and Iliamna lakes, Southwestern Alaska; J. A. Dumoulin and J. E. Gray Eds., Geological studies in Alaska by the US Geological Survey, 1995: USGS Professional Paper 1574, p. 73-81.	No	Studies elevated shorelines along L. Iliamna at two points and finds no evidence of isostatic or tectnoic deformation.
H.M. Kelsey, B.L. Sherrod, A.R. Nelson, T.M. Brocher, 2008: Earthquakes generated from bedding plane-parallel reverse faults above an active wedge thrus, Seattle fault zone, GSA Bulletin 120 no. 11-12, pp 1581-1597.	N/A	Presents detailed geomorphic, LiDAR, and seismic data depicting the complex deformation on the Seattle Fault.
R. D. Koehler, R. D. Reger, 2011: Reconnaissance Evaluation of the Lake Clark Fault, Tyonek Area, Alaska; DGGS Preliminary Interpretive Report 2011-1.	Yes (2009 draft)	Documents study of the Lake Clark Fault 150 miles northeast of Pebble near Tyonek. No evidence for offset of late Pleistocene moraines.
K. G. Mackey, K. Fujita, L. V. Gunbina, V. N. Kovalev, V. S. Imaev, B. M. Koz'min, L. P. Imaeva, 1997: Seismicity of the Bering Strait region: Evidence for a Bering block; Geology vol. 25, no. 11, p. 979-982.	No	Provides evidence for rotation of the continental crust underlying the Bering Sea.
E.S. Nadin, J.B. Saleeby, 2010: Quaternary reactivation of the Kern Canyon fault system, southern Sierra Nevada, California, Geologic Society of America Bulletin 122 (9-10) pp 1671-1685.	N/A	Presents paleoseismological and seismological evidence of normal earthquakes on the Kern Canyon Fault.
W.H. Nelson, C. Carlson, J.E. Case, 1983: Geologic Map of the Lake Clark Quadrangle, Alaska, USGS Miscellaneous Field Studies Map 1114-A.	No	Shows the Lake Clark Fault as inferred, splaying along both NW and SE shores of Lake Clark. Maps a splay joining the main fault from the north.
PLP (Pebble Limited Partnership), 2012, (3.7.3): Bedrock Geology in the Mine Study Area, Pebble Project Environmental Baseline Document 2004-2008, Chapter 3.7.3. http://www.pebbleresearch.com/download/	N/A	Describes the bedrock geology near the Pebble Prospect, including major rock units, faults, and mineralized areas.
PLP (Pebble Limited Partnership), 2012, (Ch 6): Geotechnical Studies, Seismicity, and Volcanism, Bristol Bay Drainages, Pebble Project Environmental Baseline Document 2004-2008, Chapter 6. http://www.pebbleresearch.com/download/	N/A	Sections 6.6.2 and 6.7 Describe PLP's assessment of the faults in the region surrounding the Pebble Prospect.
G. Plafker, L. M. Gilpin, J. C. Lahr, 1994: Neotectonic Map of Alaska, from Geology of Alaska – Vol G-1 of the Geology of North America (GNA-G1).	No	Overview of Alaska tectonics that includes notes on tectonic status of mapped faults. Notes offset on the Lake Clark Fault in the neogene, but no more recent evidence.
M.J. Rymer, G.G. Seitz, K.D. Weaver, A. Orgil, G. Faneros, J.C. Hamilton, C. Goetz, 2002: Geologic and Peleoseismic Study of the Lavic Lake Fault at Lavic Lake Playa, Mojave Desert, Southern California, Bulletin of the Seismological Society of America 92 (4) pp. 1577-1591.	N/A	Describes post-earthquake study of Lavic Lake Fault, showing that there is evidence of a past earthquake, though it was missed prior to the 1999 earthquake.

B.L. Sherrod, T.M. Brocher, C.S. Weaver, R.C. Bucknam, R.J. Blakely, H.M. Kelsey, A.R. Nelson, R. Haugerud, 2004: Holocene fault scarps near Tacoma, Washington, USA.	N/A	Uses LiDAR and aeromagnetic data to identify an active fault, then presents results of trenching that fault.
W.C. Steele, 1985: Map Showing Interpretations of Landsat Imagery of the Lake Clark Quadrangle, Alaska, USGS Miscellaneous Field Studies Map 1114-F.	No	Maps lineaments and other features interpreted as faults in the Lake Clark quadrangle. Shows lineaments parallel to the Lake Clark structure further to the northwest.
TNC (The Nature Conservancy), 2010: An Assessment of Ecological Risk to Wild Salmon Systems from Large-scale Mining in the Nushagak and Kvichak Watersheds of the Bristol Bay Basin. http://www.nature.org/ourinitiatives/regions/northamerica/unitedstates/alaska/explore/ecological-risk-assessment-nushagak-kvichak.pdf	N/A	Extensive analysis of potential impacts of mine development. Includes modeling of tailings dam failure.
Wardrop-NDM (Northern Dynasty Minerals), 2011: Preliminary Assessment of the Pebble Project, Southwest Alaska. Web version: http://www.northerndynastyminerals.com/ndm/Prelim_A.asp	N/A	Provides an economic analysis of several mine scenarios. It includes a 25 year mine plan with a version of tailings impoundment G with two dams, the taller of which is about 675 feet tall.

*Only papers that directly bear on seismicity at the Pebble site are marked Yes/No. Other referenced papers are marked N/A.

Executive Summary

Table ES1. Review of Pebble Limited Partnership's (PLP's) Environmental Baseline Document (EBD): Hydrologic characterization

Basic issue	Does PLP have sufficient hydrologic data and an adequate process-based understanding of the Pebble site hydrology to evaluate the potential impacts of mining on downstream waters?
Approach, data quality, and intended uses	Hydrologic data collection for the Pebble baseline studies followed accepted approaches, and the data are generally of high quality. The hydrologic modeling work presented in the EBD uses a modeling package that is not well-suited to modeling the extensive interactions between surface water and groundwater that have been observed at Pebble. The modeling is also overly parameterized and the parameters used are not always true to observed data. Thus while the calibrations demonstrate a reasonable agreement with observations, it is not clear that the model represents the physical system adequately for impact analysis.
Primary data gaps	There are limited data available on winter flows in all of the streams, and the precipitation gages appear to be "missing" between 25% and 40% of all rain and snowfall. These are both important components of the site water balance, and represent data gaps that should be filled. Extreme events are also not well-characterized, since the period of record reported in the EBD is less than four years long.
Principal findings and recommendations	The baseline hydrologic information reported in the EBD represents the foundation on which all future modeling and impact analysis will be undertaken. Based on the information presented in the EBD, the water balance model is insufficient; the period of monitoring is too short to characterize hydrologic extremes; there are numerous instances where model parameters conflict with field-measured values; and the modeling frameworks currently being used are inadequate for describing the system. These shortcomings indicate that PLP's current understanding of the baseline hydrology is inadequate to evaluate the short-term or long-term impacts of large-scale mining on the hydrology of this ecologically sensitive area. Substantial additional work is required to fill existing gaps in the baseline hydrologic data, and to develop an integrated groundwater-surface water model that is capable of simulating both baseline and future conditions.

Introduction

Any open pit or underground mine design for extracting the Pebble ore would require large-scale dewatering and discharge operations that would redistribute flows both spatially and temporally. In addition, surface impoundments required to store tailings and waste rock will necessarily limit infiltration to groundwater over their footprint. Quantifying the impacts of these changes to the hydrologic system on streamflow and salmonid spawning and rearing will be an essential part of mine development. PLP must therefore demonstrate that their understanding of baseline site hydrology (including spatial and temporal variability) is robust enough to reliably predict deviations from baseline conditions caused by mining.

This review summarizes and critiques the information presented in Chapters 7 and 8 of the EBD released by PLP in 2011 (PLP, 2011a, 2011b). Chapter 7 summarizes the surface water hydrology of the Bristol Bay watersheds. My review of Chapter 7 focused primarily on the main text, Appendix 7.2A (Hydrologic Analysis), Appendix 7.2B (Low Flow Analysis), and Appendix 7.2C (Peak Flow Analysis). Chapter 8 of the EBD summarizes the groundwater hydrology of the site, and my review of Chapter 8 focused primarily on the main text, Appendix 8.1I (Water Balance Model), and Appendix 8.1J (Groundwater Model). The other appendices in these chapters contain supporting information such as hydraulic testing results, borehole logs, interpretive cross-sections, and groundwater elevation and gradient data.

The review contained herein is necessarily limited in its scope: collectively, Chapters 7–8 and their 21 appendices constitute nearly 3,500 pages of information. As a result, the review focuses on data, model inputs and outputs, and interpretations in the EBD that raise the most significant issues for the development of a baseline site conceptual model. In particular, these issues are:

- The water balance is insufficient: inputs and outputs to the hydrologic system are not balanced based on measured data.
- The estimation of hydrologic extremes is based on a period of monitoring that is too short to characterize natural variability.
- The numerical groundwater model is over-parameterized, and there are numerous instances where model parameters conflict with field-measured values.
- The modeling software used for the numerical groundwater model is inadequate for describing the interconnected groundwater-surface water system.

Criteria for Evaluation

The criteria for evaluation of the EBD included three major components. First, I evaluated the degree to which the methods used for data collection and analysis followed standard practices. For example, I evaluated whether PLP used the proper instrumentation to collect their hydrologic data, and whether they used acceptable modeling tools and techniques to process these data. Second, I evaluated the completeness of the data. The analysis of data completeness focused on both the frequency and duration of monitoring and on the methods employed to fill any data gaps. Third, I evaluated the degree to which PLP's interpretations of the hydrologic data, where applicable, are consistent with the reported data.

Evaluation and Implications

Acceptability of Methodologies

Based on the level of review I was able to conduct, it appears that PLP used standard and acceptable methods to collect their hydrologic data. River stage was measured continuously at 26 stations using autonomous pressure transducers, and the data were converted to discharge using standard rating curve methods (e.g., Rantz, 1982). Groundwater depths were monitored monthly at over 200 locations and converted to elevations based on surveyed well casing elevations. Meteorological data were collected using autonomous weather stations, including NOAH II precipitation gages for measurement of rain and snowfall. All these data collection methods appear to be consistent with accepted methodologies (U.S. EPA, 2003).

The groundwater modeling described in the EBD was conducted using MODFLOW-SURFACT™. This model was calibrated to surface water and atmospheric inputs through a spreadsheet-based water balance model. MODFLOW-SURFACT™ is a widely accepted software package for simulating groundwater flow; however, there are two problems with the groundwater modeling in this instance. First, because the water balance outputs are the main calibration targets for the numerical groundwater model, the MODFLOW-SURFACT™ model is only as good as the water balance. As described below, the water balance has some important issues that must be addressed, which calls into question the numerical groundwater modeling interpretations in the EBD. And second, as noted multiple times throughout the EBD, groundwater and surface water are closely coupled at Pebble; water moves freely between surface and groundwater reservoirs in this area. Due to these extensive interactions, a code that more explicitly simulates groundwater-surface water interactions such as MODHMS® or MIKE-SHE® would have been more appropriate for this task. In fact, the developers of MODFLOW-SURFACT™ recommend a more integrated code for systems like Pebble that have extensive surface-groundwater interactions (HGL Software, 2012).[1]

1. The frequently asked question (FAQ) page for MODFLOW-SURFACT™ states: "MODFLOW-SURFACT™ / MODHMS® does incorporate interaction between the unsaturated zone and rivers and lakes; however, for a rigorous treatment of surface water-groundwater interactions the integrated surface water-groundwater code MODHMS® is recommended." Other codes, such as Mike-SHE®, also treat groundwater-surface water interactions more explicitly.

Data Completeness

From 2004 to the present, PLP has collected a large amount of hydrologic baseline data for the proposed Pebble project. These data include meteorological records, stream gaging records, boring log and water level data, hydraulic conductivity estimates using pumping and response tests, and seep flow data. The majority of these data were collected either continuously (e.g., meteorological and stream gaging records) or with sufficient frequency to capture inter- and intra-annual variability in hydrologic conditions (e.g., approximately monthly measurements of groundwater elevations and seep flows). Although the hydrologic data are generally complete, there are some important exceptions that limit PLP's ability to characterize baseline conditions in the Pebble watersheds. Three notable exceptions are described below.

First, although the hydrologic data have been collected from 2004 through at least 2011, the EBD only reports the data collected through 2007. This limits PLP's ability to characterize peak flows and low flows, since the uncertainty associated with estimating the magnitude of extreme hydrologic events decreases as the duration of monitoring increases. As an example, using a 10-year flood record rather than a 5-year record will cut the uncertainty on the 100-year peak flood estimation roughly in half (Dunne and Leopold, 1978). With only three complete years of monitoring reported in the EBD, the interpretations of the hydrologic system are correspondingly limited, and PLP's analyses of peak flows and low flows presented in Chapter 7 (Appendix 7.2C–D) have extremely large uncertainties. Any mine water management infrastructure must be designed to withstand extreme events, and the design criteria must rely on an adequate description of what these events might look like in the future. Mischaracterizing these extremes could therefore result in flooding of infrastructure, impoundment overflows, or unanticipated erosion. Reducing uncertainties in these estimates should have been a goal of the EBD, and including the hydrologic data collected since 2007 would have reduced these uncertainties.

Second, none of the PLP stream gages collected measurements during the winter because the rating curves developed for stream gaging could not be used for flow beneath ice (Chapter 7, p. 14). Instead, the winter flows at the PLP gages are all calculated by scaling the U.S. Geological Survey gage measurements from lower in the catchments to the contributing drainage area at each gage. Using these simple scaled flows, the EBD suggests a complete understanding of winter flows that cannot be supported by the data:

> The lowest monthly flows, and the most prolonged periods of low flows, always occurred in the late winter (February through April) at all stations and in all years of the study period. (Chapter 7, p. 16)

While scaling discharge to drainage area is a generally acceptable method for estimating flows in ungaged headwater catchments, this methodology creates a substantial data gap in the coupled groundwater-surface water system at Pebble because flows in gaining and losing reaches along these streams cannot be estimated with these simple scaling relationships. Since the majority of the streams are ungaged during the winter, there is in fact significant uncertainty surrounding the magnitude of winter flows, and in particular where and when the headwater streams might become dry during the winter (if they go dry at all). This distinction could be critical for characterizing salmonid habitat under baseline conditions, and for understanding the impacts to this habitat under a mining scenario.

Third, although the meteorological data were collected continuously, the water balance model indicates that the measured precipitation may underestimate total precipitation by 25% to 40% (or alternatively, the stream gaging records overestimate discharge by a similar amount; see below). For example, the precipitation applied to the water balance for the SK119A catchment is nearly 40% higher than the highest precipitation observed at the Pebble 1 meteorological station (54.5 in. vs. 39 in.), even though these two locations are at nearly the same elevation and relatively close to one another. This correction occurs despite the use of a NOAH II precipitation gage, which is designed to minimize undercatch of frozen precipitation and appears to do a good job of measuring winter precipitation at the site, based on comparisons with snow course data (Appendix 7.2D, p. 28). The fact that the water balance requires an additional 40% correction factor to the measured precipitation demonstrates that there may be a significant problem with the completeness of the precipitation records and the accuracy of the water balance (U.S. EPA, 2003). A mine plan that relies on these measured precipitation records as a basis for a site water balance will either be incorrect or have a very high uncertainty. Again, this degree of uncertainty may be too high for designing mine water management infrastructure, with the potential for inadequate water management planning as a result.

Significant Findings

Chapter 8 of the EBD presents the water balance and numerical hydrologic models that PLP has developed to simulate baseline conditions at Pebble. These hydrologic models are presented in a way that gives the impression of a well-characterized hydrologic system. Monthly flows are well approximated by the water balance model, and spatial and temporal patterns of flow are matched by the numerical groundwater model (Figure 1). However, when the components of these models are examined in detail, it is questionable whether PLP actually has an adequate understanding of the hydrologic system. Examples of these shortcomings are described below.

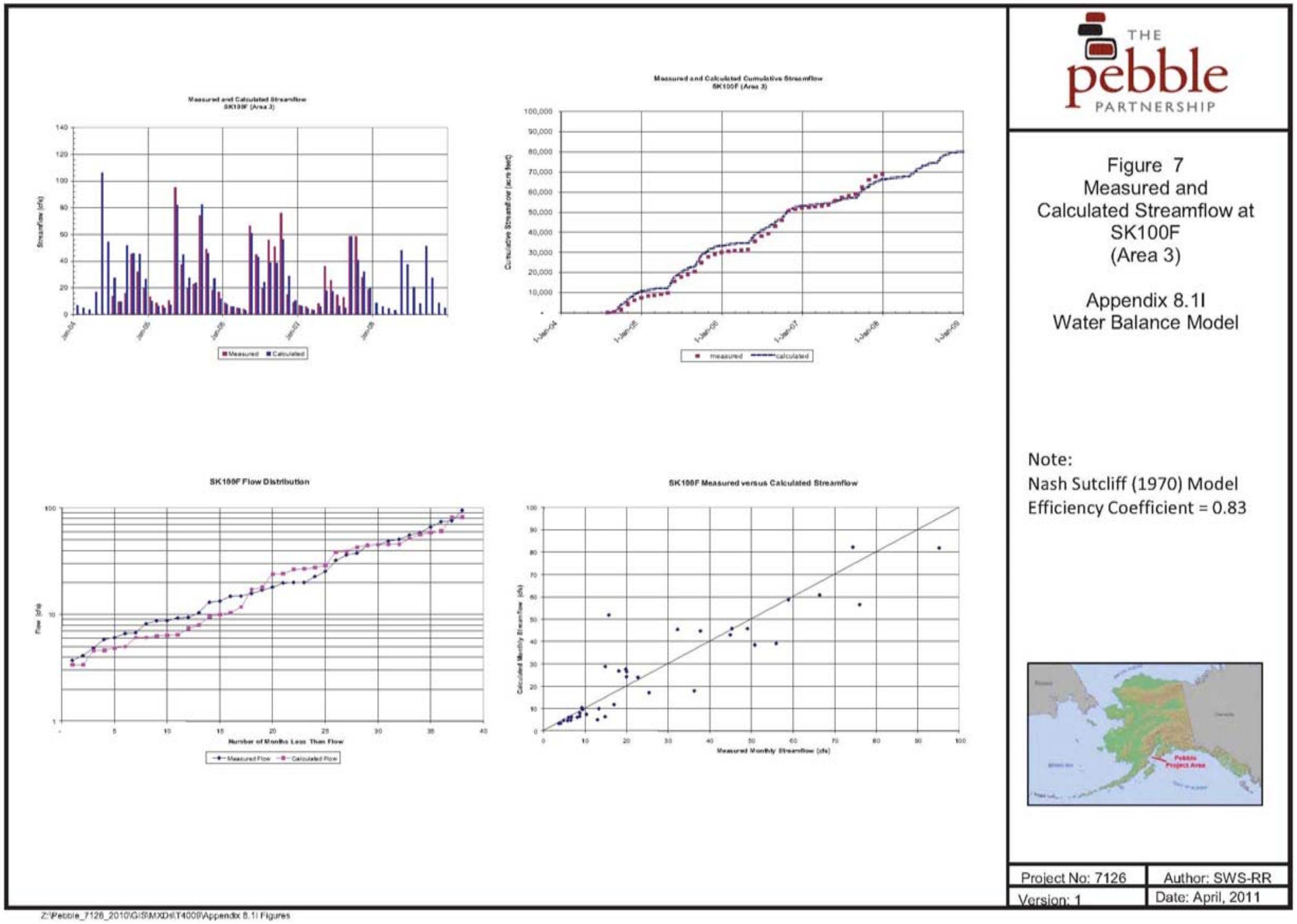

Figure 1. Water balance results for SK100F. Note that there is general correspondence between the water balance predicted and observed flows.

Source: PLP, 2011b.

1. Mismatch between measured precipitation and streamflow

Despite an extensive hydrologic data collection program, the only measured parameters used in the water balance are streamflow and groundwater elevations. All other variables are adjusted so that the remaining inputs and outputs to the hydrologic system match these parameters. From Chapter 8, page 26 of the EBD:

> The water balance was calibrated to the cumulative water volumes at selected stream gages by adjusting climate variables (precipitation and evapotranspiration). The estimated division of flow as immediate runoff, groundwater recharge, and groundwater discharge was then refined by adjusting the groundwater recharge and discharge rates to produce a match between estimated and measured monthly values of streamflows and groundwater levels.

Using this method, the modeled inputs and outputs to the hydrologic system are essentially guaranteed to balance, as presented in Appendix 8.1I. However, given the mismatch between *measured precipitation* and *measured streamflow* as described above, it is questionable whether this calibrated water balance paints a realistic picture of the hydrologic system. The water balance model requires between 40 and 55 in. per year of annual precipitation (an amount that varies by sub-catchment) in order to supply enough water to the system to match the measured streamflow. Yet the measured annual precipitation over the three years of monitoring is only 30–39 in. (EBD, Chapter 2). Thus, either the measured precipitation at the site is 25–40% too low or the measured streamflow at the site is 25–40% too high. It is nearly impossible to tell based on existing data which of these errors underlies the hydrologic imbalance at the site. However, given the magnitude of the discrepancy, it is clear that PLP must resolve this issue.

2. Calibration vs. validation

The second issue is that the calibration between the water balance and numerical groundwater models is circular. In other words, the two models are calibrated to one another, but there is no independent calibration to data, which means that it is possible that neither model is simulating the actual hydrologic system. This is evident from the first page of the numerical groundwater modeling appendix:

> The flow rates calculated by the calibrated Groundwater Model were then compared to the corresponding flow rates calculated with the Water Balance Model. The purpose of this phase of the calibration was to validate that the flows estimated by the Water Balance Model were hydrogeologically feasible, and to gain insights about potential refinements that may be appropriate for the Water Balance Model. (Appendix 8.1J, p. 1)

The remainder of Appendix 8.1J presents the results of the numerical groundwater model calibration, reporting statistics on goodness-of-fit, root-mean-square (RMS) errors, etc. However, these calibration statistics reflect the correspondence between the numerical groundwater model and a flawed water balance because *measured precipitation* is too low to explain *measured streamflow*, as described above. In addition, the numerical groundwater model is over-parameterized relative to the amount of data available. The model domain is broken into 644 hydraulic conductivity "zones," for which the hydraulic conductivity values used in the model have little to no relationship with field-measured conductivities. For example, Figure 2 is a plot of the hydraulic conductivity values used in the groundwater model vs. field-measured hydraulic conductivities. In general, the model values do not correspond at all to the field-measured values, indicating that the calibrated groundwater model ignores field-measured data.

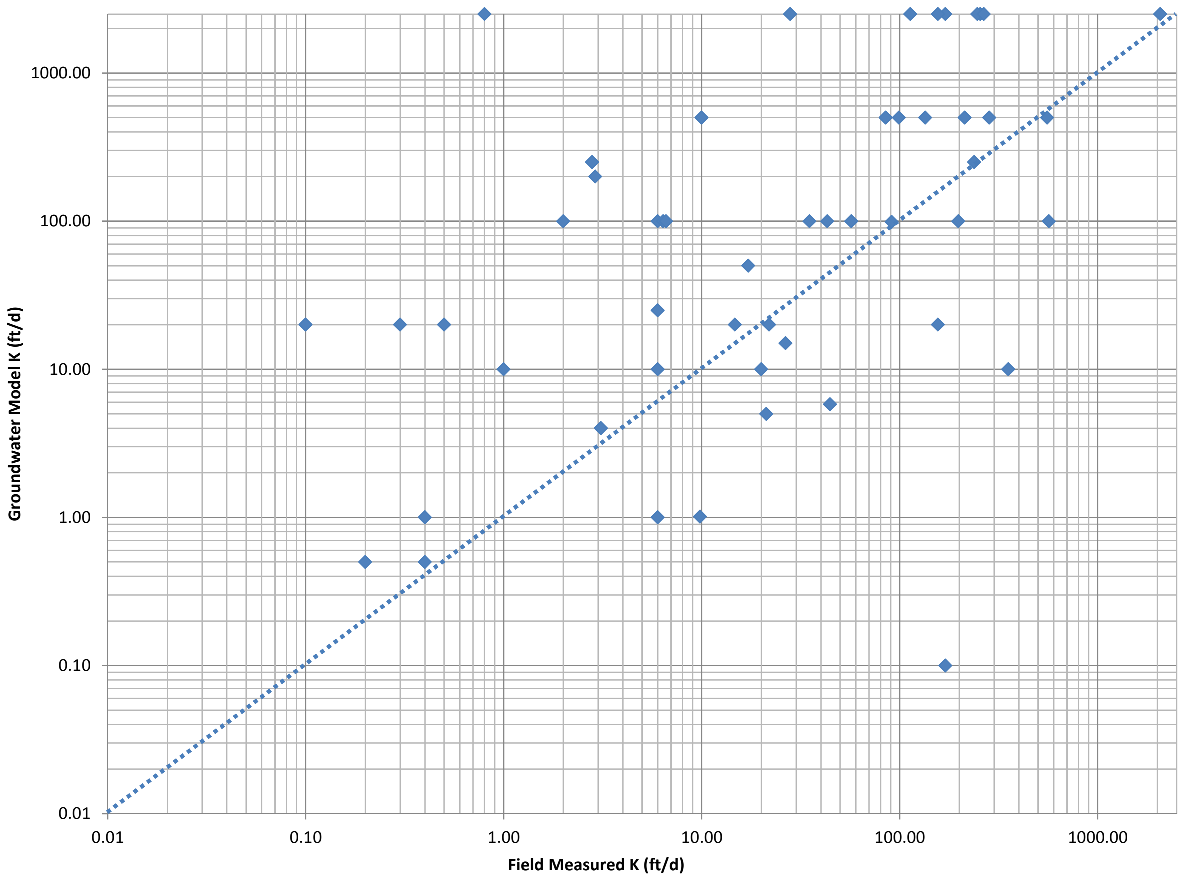

Figure 2. Comparison of field-measured hydraulic conductivity values to values used in PLP's groundwater model.

Data source: PLP, 2011b.

Thus, while the EBD presents a numerical model that appears to be well-calibrated, the number of parameters and the values required to achieve this calibration often have little relation to field-measured data. This could have significant implications when using this calibrated model to evaluate changes in hydrology related to mining. In particular, since the model inputs are not true to available site data, the model may have no predictive capability at all when used for impact analysis (U.S. EPA, 2003).

3. Influence of faults on groundwater flow

Third, the groundwater model does not incorporate the influence of faults on bedrock groundwater flow. The available data from tests in deep boreholes indicate that at least one of the major identified faults crossing the deposit area (the "ZE Fault") exerts a strong control on groundwater flow: hydraulic heads rise approximately 20 ft across this fault, which indicates that groundwater is under pressure beneath this fault zone (Figure 3). This fault and other deep bedrock faults that would be intersected by a pit are clearly influencing groundwater around the deposit area, and could be conduits for groundwater flow. This suggests that these faults could make it difficult to maintain a capture zone around the pit both during and after mining. As currently presented, the groundwater model makes no mention of faults at all, calling into question PLP's ability to predict the impacts of mining on groundwater. PLP must model the influence of major faults on groundwater flow, particularly near the pit where they could represent conduits for contamination to escape to downgradient surface water and groundwater resources.

4. Simulation of groundwater-surface water interactions

The hydrologic system at Pebble is not cleanly segmented into separate groundwater and surface water reservoirs, and should not be modeled as such. The software used by PLP (MODFLOW-SURFACT™) is a well-recognized program for simulating groundwater flow; but given the extensive interaction between groundwater and surface water at Pebble, a different modeling package would be more appropriate. For example, flow between surface water and groundwater in MODFLOW-SURFACT™ requires a "stream conductance" parameter, which controls the rate at which surface-groundwater exchange occurs across stream beds. In the PLP-calibrated MODFLOW-SURFACT™ model, the values of this stream conductance vary over approximately five orders of magnitude, but this parameter is completely unconstrained by field measurements. Other modeling packages that allow surface water-groundwater exchange to occur based on field-measured parameters could have been used, and this would make model results both better constrained by available data and more useful for predicting mining impacts.

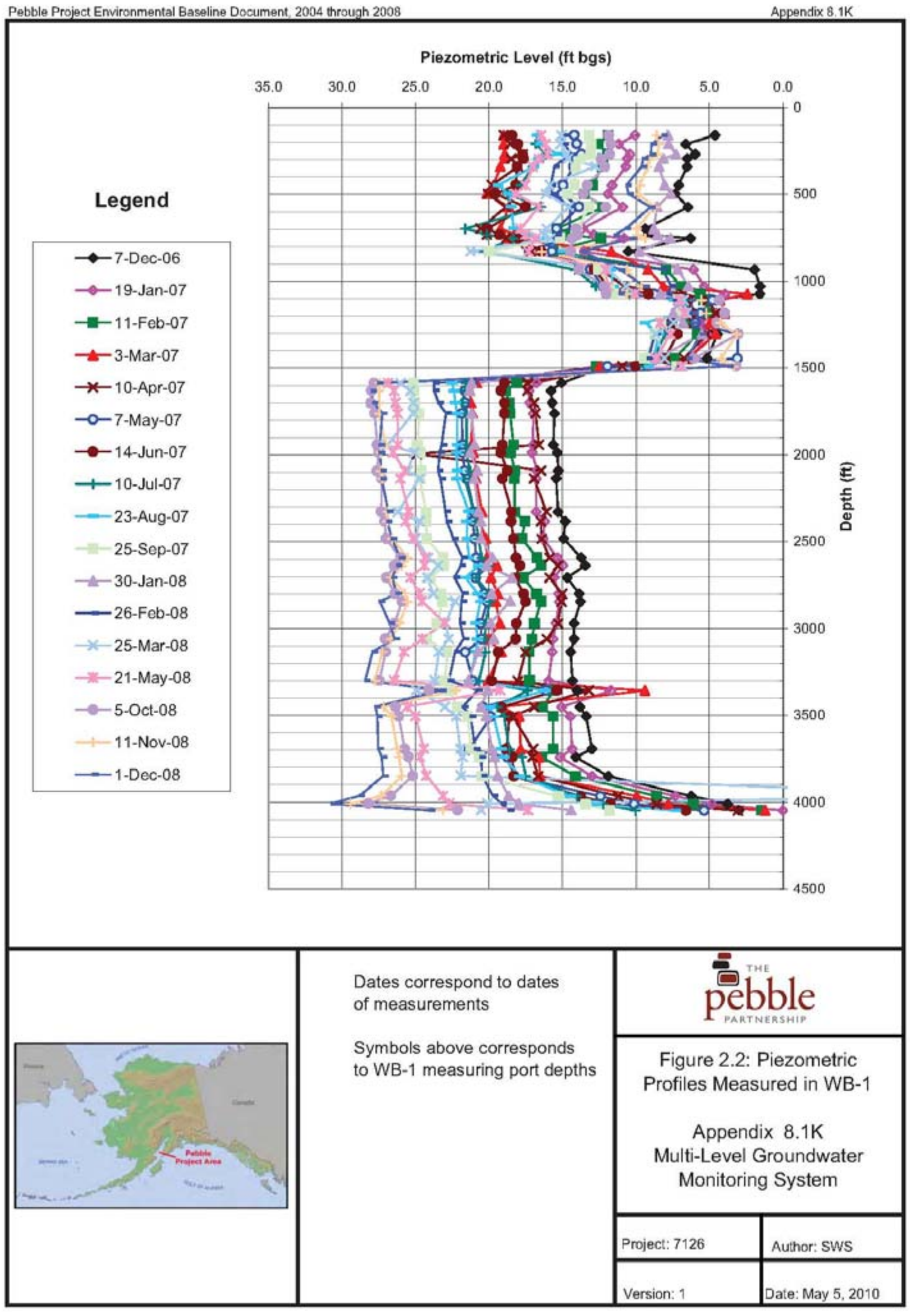

Figure 3. Hydraulic heads (piezometric levels) measured across ZE fault. Note significant change in head across the ZE fault (~ 1,500 ft), demonstrating the control of this fault on groundwater flow.

Source: PLP, 2011b.

5. Calibration period and hydrologic extremes

Even if the water balance and modeling issues described above were resolved, the hydrological modeling presented in the EBD is based on a calibration period of only three years, which is too short to characterize the range of extreme events that might be seen at Pebble over the mine lifetime. Even over this short model calibration period, the model begins to fall apart when stressed:

> Plots of residuals versus time (Appendix 8.1J) signify that the residuals at some wells start to increase during 2006 and 2007, which indicates that the model needs to be improved to simulate the conditions for these years in some areas (e.g., P05-07D, SRK-5M, and MW-3 in Upper SFK; MW-2D, GH04-30, and GH04-33 in Lower SFK; and MW-7 and MW-8 in NFK). (Chapter 8, p. 66/2500)

The years 2006 and 2007 were drier years than the earlier years of monitoring. The observation that head residuals increase with time indicates that while the numerical model may be adequately approximating the water balance during the early calibration period, it is not simulating conditions under hydrologically stressed conditions. This indicates that the modeling tools currently being used by PLP may also not be the right tools to simulate changes in hydrologic regimes under mining scenarios, or under a changing climate.

Conclusions

As described in Chapters 7 and 8 of the EBD, the hydrologic system at Pebble is complex. It is characterized by spatially and seasonally variable interactions between surface water and groundwater, and by strong seasonal variability in precipitation and flows. Extraction of the Pebble ore body would require large-scale dewatering and discharge operations that would redistribute flows both spatially and temporally. Before PLP can evaluate the impacts of these mine-related dislocations on the hydrologic system, they will need an integrated set of data and models that adequately describes baseline conditions. Based on my review of the EBD, PLP does not yet have the tools to do this. While their baseline data are generally of high quality, there are a number of important data gaps that need to be filled. Equally important, the modeling results reported in the EBD suggest significant flaws in the conceptualization of the site water balance, groundwater-surface water interactions, and groundwater flow. All of these shortcomings must be corrected before PLP can model the potential impacts of the proposed Pebble mine operations on the hydrology of these watersheds and the fishery these waters sustain.

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